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PLANFORM CYCLICITY IN AN UNSTABLE REACH: COMPLEX FLUVIAL RESPONSE TO ENVIRONMENTAL CHANGE

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ABSTRACT

Long- and short-term channel changes are documented and analysed for a historically unstable reach of the River Severn at Llandinam, mid-Wales. Long-term changes (the last 150 years), reconstructed from 10 archival sources, are characterized by channel planform switching between meandering (1836–1840 and 1948–1963) and braided (1884–1903 and 1975–present) phases. Short-term changes, monitored by detailed planform surveys over a 2·5 year period, showed smaller-scale channel adjustments involving channel switching, bar accretion and channel expansion. Phases of braiding at Llandinam have been triggered by extrinsic controls, primarily flooding, but intrinsic controls (floodplain sediments, planform evolution and channel gradient) have been influential in priming the reach prior to destabilization. Flow regulation on the River Severn since 1968 has partly frozen the planform of the contemporary braid zone. Management of channel planform adjustments, where environmental change is phased in over time, must be informed by a knowledge of the potential for triggered planform switches. In addition, the effects of environmental change on fluvial systems are often historically contingent upon the state of the channel at the time of impact. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: channel instability; braiding; flooding; flow regulation; planform freezing

INTRODUCTION

Since Leopold and Wolman (1957) proposed the tripartite division of channel planforms (straight, meandering and braided), there has been considerable attention paid to the processes responsible for channel change and the classification of channel planforms. It is apparent that many channel patterns do not fit ideally into Leopold and Wolman's classification. There is more complexity between (especially the meandering–braided transition) and within (especially braided) the different categories than originally envisaged. As more research is undertaken on river systems, new planform types are being identified: for example, wandering rivers (Neill, 1973; Church, 1983), sinuous/non-sinuous braided (Brice, 1984), divided (Hitchcock, 1977) and anastomosing (Smith and Smith, 1980; Knighton and Nanson, 1993). More recently, Nanson and Knighton (1996) have proposed a six-fold classification of anabranching systems based on stream power, sediment texture and river morphology.

Channel changes may be defined at two levels: first, extrinsic (cf. first order; Bull, 1991) which occur in response to systems changes involving for instance climate change, tectonics and human activity: and second, intrinsic (cf. second order; Bull, 1991) which are inherent in the river regime and involve channel migration, cut-offs, avulsion etc. Throughout the Quaternary, river systems have adjusted to fluctuations in stream discharge and sediment load. Periods of high stream discharge have been associated with the development of high amplitude and long wavelength meanders (Dury, 1970; Leigh and Feeney, 1995), the initiation of braiding (Rust and Nanson, 1986), and phases of aggradation (Young *et al.*, 1986; Wells, 1990) and incision (Rumsby and Macklin, 1994). In contrast, channel metamorphosis from braiding to meandering (Rust and Nanson, 1986) and phases of incision (Starkel, 1981) have been related to periods of low stream discharge. Such pattern changes may be difficult to assign to extrinsic or intrinsic causes, since phases of high or low discharge may be regarded as inherent within particular regimes (Erskine and Warner, 1988) as much as one-way environmental changes.

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Although general fluvial responses to both extrinsic and intrinsic systems changes have emerged, it is also apparent that similar systems changes can invoke disimilar fluvial responses. For example, aggradation is commonly associated with increased precipitation (Young et al., 1986; Wells, 1990) and tectonic subsidence (Starkel, 1991; Passmore et al., 1992) but it has also been noted in association with decreased precipitation (Knox, 1983) and tectonic uplift (Schumm and Parker, 1973). Fluvial responses are further complicated by the apparent existence of thresholds between pattern states, with sudden changes occurring when critical limits are exceeded (Schumm, 1974). Thresholds might be exceeded because of small intrinsic changes (e.g. channel gradient increase by meander cut-off) or larger extrinsic changes (e.g. stream power increase by high magnitude flood). Finally, fluvial systems frequently respond to multiple forcing variables: for example, McEwen (1989) and Macklin and Lewin (1993) have demonstrated the importance of both climate change and human activity on fluvial responses.

Whilst considerable efforts have been exerted in predicting intrinsic channel pattern changes, as manifested in rates of planform evolution in meandering reaches, there remains the problem of identifying responses to alternative extrinsic forcing factors, especially if these are liable to produce threshold changes in channel pattern (metamorphosis in the sense of Schumm, 1969). Such factors include changes in drainage basin hydrology and sediment load (Nanson and Knighton, 1996), reservoir impoundment (Petts, 1979) or local river channelization (Brookes, 1987). In addition, the impact of global climate change resulting from human-induced changes to atmospheric composition may alter flood and drought frequency (Newson and Lewin, 1991). As will later be shown, such extrinsic changes may impact on channel patterns at particular stages in a cycle of development. Thus meander development may have reached a particular stage of development when impacted by a change in hydrological regime or sediment supply. Alternatively, channels recovering from the effect of large floods may respond differently according to the stage of recovery that has been reached.

The objective of the research reported here is to present an assessment of factors leading to pattern change at a single site over an extended time period during which environmental changes have occurred. The paper documents long-term (<150 years) and short-term (<3 years) channel changes in a short unstable reach on the River Severn. This reach changes between a meandering and a multi-thread planform style, so it provides an excellent opportunity to examine causal factors responsible for such a planform adjustment, and to assess whether short-term observable changes are historically contingent to the extent that the impact of environmental change requires consideration of longer term cyclic developments.

THE LLANDINAM INSTABILITY ZONE

The River Severn rises on the eastern flank of the Cambrian Mountains (610 m), and flows in an easterly direction for the majority of its course through Wales (Figure 1A). The Llandinam instability zone lies in the upper Severn catchment some 35 km downstream from the river's source. Although having a largely natural flow regime, since 1968 one of the upper Severn's major tributaries, the Afon Clywedog, has been regulated by means of the Clywedog Dam. This regulation and flood control structure has significantly reduced the magnitude of peak flows in the upper Severn catchment in the last 30 years (Higgs, 1987).

The glacially over-deepened upper Severn Valley is partly infilled with thick Quaternary deposits. Upstream of Llanidloes, stratified scree and head deposits are dominant, but downstream of Llanidloes deposits are mainly fluvio-glacial in origin, reflecting the change from an ice-proximal to a fluvio-glacial environment (Humphries, 1979). The upper Severn alternates between reaches where the main channel has a low sinuosity (<1·5), stable, bedrock-controlled and entrenched (locally up to 5 m) course, and reaches where the main channel has a high sinuosity (>2) course, with highly erodible composite banks, and is thus frequently laterally unstable across its floodplain (average width 0·5–1 km). The 2·0 km Llandinam instability zone lies in the latter type of reach but is bounded upstream by an entrenched (by *c*. 2·5 m), locally bedrock-controlled reach. It is also bounded downstream by a short entrenched reach (*c*. 2·0 m) adjacent to Llandinam Bridge (Figure 1A, B).

The 2·0 km instability zone is currently dominated by a 500 m multi-thread reach (National Grid Reference SO 022872) which historically has frequently had a planform that cannot be easily assigned to one of the 'conventional' planform types: straight, meandering or braided (Leopold and Wolman, 1957). Although a bifurcating channel reach (Figure 1C), it does not exhibit large, unstable, overlapping, mid-channel gravel bars

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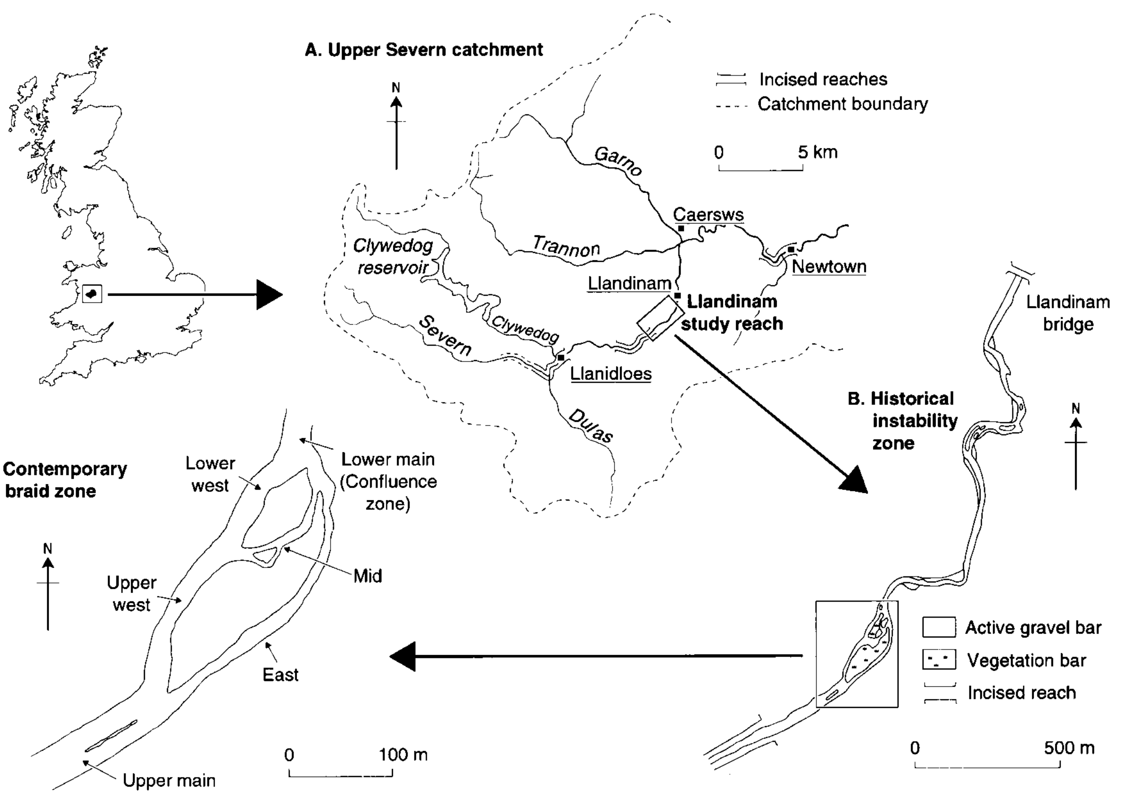

Figure 1. (a) The upper Severn catchment area showing the location of the Llandinam study reach. (b) The historical instability zone in 1984. (c) The contemporary braid zone in 1993

as found, for example, in many high latitude environments (Rust, 1972). The divided trunk stream channel more closely resembles the 'wandering gravel rivers' as described by Neill (1973) and Church (1983) or the 'sinuous braided channel' as described by Brice (1984). For the purposes of this study, and to avoid introducing a new descriptive term, periods of multi-thread channel activity at the Llandinam reach will be described as braiding.

DATA SOURCES AND METHODOLOGY

Two main data sources have been used in this study for the reconstruction of planform evolution at Llandinam. First, historical map and aerial photograph analyses have permitted long-term planform development since 1836 to be established; and second, repeat channel surveys and morphological mapping of the reach over a three year period allow a greater resolution of planform adjustment to be monitored than is possible from the archival sources alone, albeit over a relatively short period of time.

Cartographic and aerial photograph archives have been commonly employed in the analysis of channel change (e.g. Hooke and Kain, 1982; Lewin, 1977, 1983, 1987), although their usefulness and applicability are subject to certain qualifications. Ordnance Survey maps dating from the mid-nineteenth century are amongst the most accurate (Harley, 1965, 1975), but in common with all map and aerial photograph sources (unless specifically commissioned) they can only provide an arbitrarily timed 'snapshot' of channel morphology (Passmore *et al*., 1993). Particular problems are associated with map sources; precise survey dates are often not known, sometimes not even to the nearest decade (e.g. 1:10 560 provisional edition at Llandinam), and map revisions (e.g. 1963 2nd edition) are frequently selective in the detail updated. Despite these obvious limitations, cartographic and aerial photograph archives remain a valuable data source for assessing the evolution of the landscape on a decade to century timescale. Table I summarizes the map and aerial photograph

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Table I. Ordnance Survey map and aerial photograph sources used in this study

Map source	Date (approx)	Scale	Photo source	Date	Scale
1″ Series	1836	1:63 360	RAF	24 March 1948	1:10 000
Tithe Map	1840	Unknown	RAF	11 May 1951	1:10 000
1st Edition 6″	1884	1:10 560	OS	6 May 1975	1:10 000
2nd Edition 6″	1903*	1:10 560	MAL	16 April 1981	1:10 000
Provisional 6″	1963†	1:10 560	Storey	24 April 1984	1:10 000
Metric	1981	1:10 000			

* First edition revision 1901
† First edition revision before 1930

Table II. Morphological changes in the 2·0 km instability zone 1836–1984. Figures in Roman type refer to data derived from published maps, and figures in italic type refer to data derived from aerial photographs

Date	Active gravel area (m^2)	Vegetated area (m^2)	Bar area (m^2) (Number)	Braid bar area (m^2) (Number)	Channel area (m^2)	Sinuosity*	Total channel environment area (m^2)
1836	n.d.	n.d.	n.d. (0)	n.d. (0)	67 714	1·26	67 714
1840	n.d.	n.d.	n.d. (0)	n.d. (0)	71 143	1·50	71 143
1884	51 455	0	16 777 (7)	34 678 (4)	53 319	1·78	104 774
1903	40 571	18 676	31 022 (7)	28 226 (6)	43 510	1·78	84 081
1948	*70 620*	*0*	*70 577 (6)*	*43 (2)*	*41 484*	*1·21*	*112 104*
1951	*63 934*	*18 595*	*82 294 (6)*	*235 (1)*	*45 506*	*1·22*	*109 440*
1963	1142	35 037	1142 (1)	35 037 (1)	45 029	1·22	46 171
1975	*19 878*	*16 087*	*22 453 (5)*	*13 512 (6)*	*55 891*	*1·65*	*75 769*
1981	*6627*	*14 152*	*4043 (7)*	*16 736 (8)*	*53 589*	*1·75*	*60 216*
1984	*12 398*	*13 096*	*7501 (8)*	*17 994 (10)*	*47 602*	*1·85*	*60 000*

* For dates when planform is braided (1884, 1903, 1975, 1981, 1984), sinuosity is calculated as 'total sinuosity P' (see Robertson-Rintoul and Richards, 1993)

sources used to reconstruct this longer term planform evolution at Llandinam. For each map edition or aerial photograph sortie, channel margins, areas of active gravel (i.e. unvegetated gravel) and all vegetated islands were digitized and transformed to a common scale (1:10 000) using ARC/INFO. Once at a common scale, quantified values (m^2) of the digitized features were abstracted and these are summarized in Table II. The precision of this method was confirmed through repeat digitizing of selected river reaches: displacement errors were always less than 2·00 m and typically less than 1·00 m. In the context of channel change at Llandinam these displacements are usually less than 1 per cent of the observed channel movement between available archive sources.

Assessing short-term planform change by repeat ground survey has, historically, been a less commonly employed method amongst geomorphologists, probably reflecting the labour and time involved in such an approach. Continuous monitoring of changes in the fluvial system has usually focused on single bar forms (Hooke, 1986; Nanson, 1980; Werritty and Ferguson 1980), point bank erosion (Lawler, 1992), or meander evolution within single thread channels (Lewin, 1976). Ground survey studies over several years of multi-thread systems are relatively rare (Martin and Church, 1995; Macklin *et al*., 1998). Ground survey of the 500 m Llandinam braid zone initially involved a theodolite EDM survey of 63 control stations marked by wooden pegs spread evenly throughout the reach. Channel margins, bar forms, islands, pools and riffles were then surveyed by tape transect and theodolite EDM from these control stations. During the study period (1990–1993), several control stations were lost as a result of unpredictably rapid bank erosion, but new stations were established to

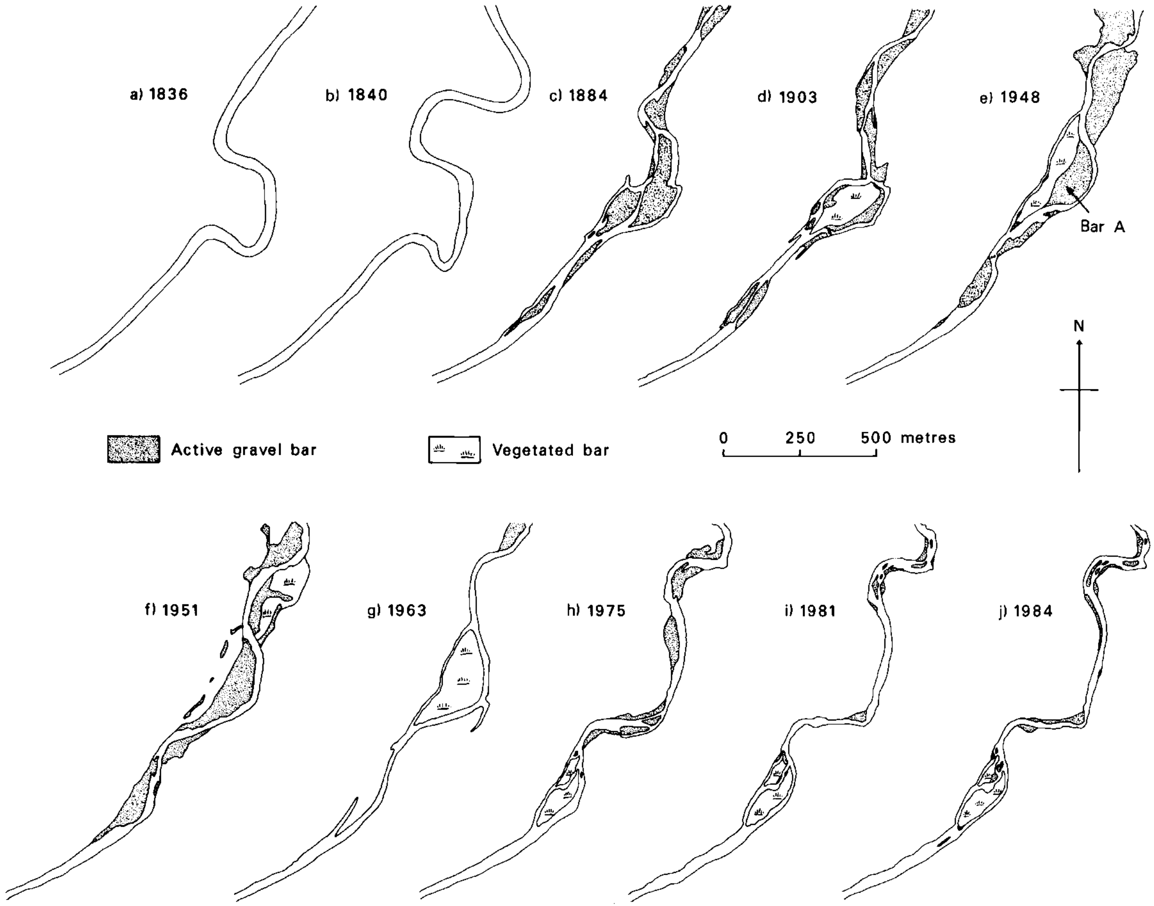

Figure 2. Channel changes in the historical instability zone from 1836–1984. See Table I for archive sources

replace them. The network of control stations ensured that the full morphology of the study reach could be monitored at all scales, from an individual bar form up to the planform of the entire braid zone.

LONG-TERM PLANFORM EVOLUTION

Figure 2 summarizes the channel planform (channel margins and bar forms) of the Llandinam instability zone for 10 dates (nine time periods) over the last 150 years. Two distinct channel planform types have alternated at Llandinam over the last 150 years; there have been two periods of braiding (1884–1903 and 1975–1981–1984) and two periods of channel meandering (1836–1840 and 1948–1951–1963). Figure 3 plots the positions of the meandering 1840 and 1963 channels with the braided channels in 1884 and 1984.

In 1836, a single thread channel occupied the study reach with one near-symmetrical meander loop developed in the centre of the reach (Figure 2a). Areas of active gravel and vegetation are not marked on the 1836 map, thus limiting the effective interpretation of channel stability at that time. However, the relatively high channel sinuosity (1·26; Table II), the erodible bank materials and palaeochannel evidence at this site would strongly suggest that the channel in 1836 was laterally unstable and actively migrating across the floodplain. Evidence for this assertion is provided by the 1840 Tithe Map, where channel sinuosity had increased (1·50) by the development of a second symmetrical meander loop downstream of the first (Figure 2b).

The first major planform change (metamorphosis in Schumm's terminology) had occurred by 1884, with the meandering planform replaced by a braided planform. The location of the braiding was coincident with the two meander loops present in 1840 (Figure 3); the significance of this braiding/meandering coincidence is

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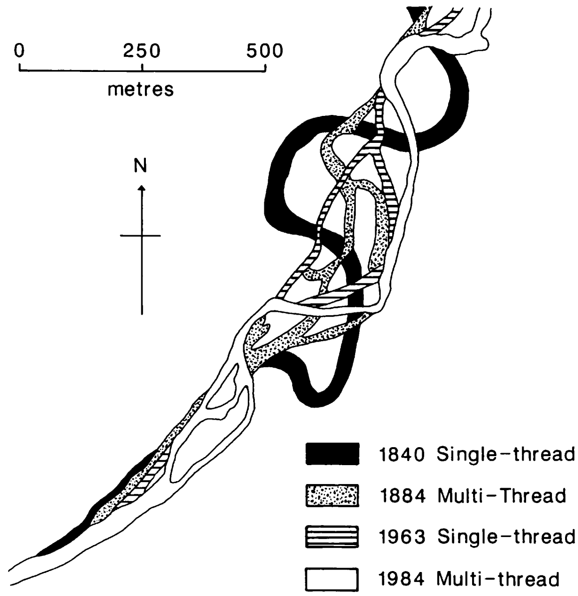

Figure 3. Overlay of historical instability zone channel positions showing the relative location of braid channel (1884 and 1984) with respect to meandering channels (1840 and 1963)

considered later. The nature of channel braiding in 1884 is comparable, albeit at a much smaller scale, with patterns of braiding in other gravelly rivers: large, overlapping, mobile medial bars with significant areas of active gravel at the channel margins (Smith, 1974). Areas of active gravel were large, constituting 49 per cent of the total channel environment (active gravel area + channel area), with 67 per cent of the active gravel stored within three medial bars, and the remaining 33 per cent within lateral bars largely in the downstream section of the reach. The second edition six-inch map demonstrates that the Llandinam reach was also braided in 1903 (Figure 2d). Although no intermediate archival evidence is available, the planform morphology in 1903 suggests that the braiding had persisted throughout the 19 year period since 1884. Areas of active gravel were still relatively large, but were 20 per cent lower than in 1884. Although large point and lateral bar deposits still dominated the downstream section of the reach, newly vegetated areas had increased from $0\,m^2$ (1884) to $18\,676\,m^2$ (1903). This increase was accounted for by the coalescence, and subsequent colonization by vegetation, of two medial gravel bars. The reduction in active gravel area and vegetation colonization of two medial bars indicate an overall stabilization of the instability zone at the turn of the century.

The second significant planform change had occurred at Llandinam by 1948, the braided planform replaced by a low sinuosity (1·21; Table II) single thread channel with large point bar deposits (Figure 2e). Although there are few similarities between the channel and bar patterns in 1903 and in 1948, the main channel in 1948 cut across the area that contained the coalesced vegetated bar in 1903. Without additional intervening archival evidence it is impossible to reconstruct the precise planform change during this 45 year period, but there are a number of possibilities. First, the 1903 coalesced vegetated bar continued to grow and stabilize, gradually blocking either the west or the east braid channels. The remaining open channel, having captured the total discharge of the river and thus having a higher stream power, laterally migrated back across the vegetated bar. Second, a major channel avulsion occurred bisecting the vegetated braid bar. Such an avulsion may have occurred during a flood event or as a result of simultaneous sediment choking of both east and west braid channels (cf. Ferguson, 1993; Leddy et al., 1993). The switch from a braided to a meandering planform was associated with a 75 per cent increase in active gravel area, stored exclusively within point and lateral bar deposits. Although the 1948 study reach is dominated by a single thread meandering channel, bar A is strictly speaking a braid bar since it is bounded on all sides by channels; a small chute channel runs to the west side of this bar (Figure 2e). The southern half of this chute channel matches the location of a 1903 braid channel, and therefore the chute channel is most likely the remnant channel from the earlier braided planform. It is worth

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recalling that initial lateral channel movement in early stage meandering can be very rapid (Lewin, 1976), creating large spreads of gravel which may then become vegetated.

The study reach in 1951 had the same meandering form as evident in 1948 (Figure 2f). The morphology of individual meander loops had altered slightly but the overall reach sinuosity had changed little (1·22; Table II). Although three of the point bars had increased in area, the overall active gravel area was reduced, largely as a result of vegetation colonization. The small chute channel evident in 1948 was still present in 1951, but was discontinuous, as a result either of a low main channel discharge at the time of survey or of sediment choking the chute channel thus preventing continuous water flow. The chute channel/bar association was still evident in 1963 (Figure 2g), with a broadly similar meandering planform to that seen in 1948 and 1951. Virtually no active gravel was present in the reach (Table II); this may be a genuine reflection of the sediment dynamics prevalent at the time or may be a result of cartographic rationalization in the map revision process. (NB The reliability of the 1963 1:10 560 provisional edition map series has been mentioned earlier.) However, the channel planform represented on the 1963 map illustrates evidence of channel evolution since 1951. For example, the upstream limb of the meander loop associated with bar A has translated downstream 50 m and a chute channel has developed in the upstream section of the reach. Although the dating control of the 1:10 560 provisional edition is uncertain, the channel margins on this map reflect the planform situation at some point between 1951 and 1975.

A third significant planform change had occurred in the Llandinam instability zone by 1975 with a small (500 m long) braided zone developed in the upstream section of the reach (Figure 2h). The braid zone is constructed around two vegetated islands with three small medial gravel bars situated within the braid channels. (NB The term ‘island’ in this paper is applied to mid-channel vegetated bar forms that are not submerged at bankfull stage (Brice, 1964), whereas the term ‘medial bar’ is applied to mid-channel gravel bars that are submerged at bankfull stage.) Downstream of the braid zone the channel pattern is broadly similar to the meandering 1963 channel pattern, but the channel has shifted locally by up to 100 m. The chute channel/bar association present in 1948, 1951 and 1963 is absent but large areas of active gravel are still stored in lateral and point bars, and it is likely that this material was derived from extensive bank erosion during the braid zone formation.

The 1975 braid zone is centred some 500 m upstream from the braided zone evident in 1884 and 1903 (Figure 3), but is coincident with active bar forms evident from archival sources since 1884 (Figure 2, Table III). In 1884 an elongate medial bar was present with the dominant braid channel to the east of the bar. By 1903 a lateral bar had formed on the east bank, adjacent to the medial bar, thus funnelling the river flow through a narrow channel between the two bars. These bar forms had changed markedly by 1948; the lateral and medial bars had been replaced by two lateral bars on the west bank, one centred some 100 m downstream of the 1903 bar forms and one centred at the 1903 medial bar location. These two lateral bars had coalesced by 1951 to form a single lateral bar. The period from 1884 to 1951 was associated with a steady rise in active gravel area and bar form development in this part of the instability zone, indicating a gradual increase in channel activity in this zone. This trend was frequently in marked contrast to downstream parts of the reach where channel activity was decreasing, for example, between 1884 and 1903 where the medial bars coalesced and were stabilized by vegetation. The 1963 provisional edition map shows no evidence of any bars at this location, but, as discussed earlier, this may not be a genuine reflection of the actual conditions prevalent at the time. The 1963 map does, however, illustrate an interesting feature at this location: a chute channel cutting across the floodplain. This chute channel is a re-exploitation of the braid channel that flowed to the west of the 1884/1903 braid bar at this location. The existence of this chute channel was noted by Thorne (1978) in 1969, and by 1975 the chute channel had become the upper west channel of the contemporary braid zone.

The overall planform at Llandinam remained broadly similar in 1981 and 1984 to the braided planform that had been established by 1975. In 1981 and 1984, the form of the two vegetated islands remained but their areas had been successively reduced (Table III). The reduction in vegetated area was matched by a steady increase in active gravel area (Table III), particularly in the west and mid-braid channels. The dimensions of the braid channels did not remain constant between 1975 and 1984: the mean width of the east channel steadily reduced from 21·8 m (1975) to 14·3 m (1981) and finally to 9·7 m (1984). It is difficult to assess whether this reduction in channel width was a genuine response to increased flow capture by the west channel, thus reducing the flow in the east channel, or whether it merely reflected differing flow stages at the time of photography (Table III). Field

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Table III. Morphological changes in the 500 m braid zone 1836–1993. For long-term study data, figures in Roman type refer to data derived from published maps and figures in italic type refer to data derived from aerial photographs

Date	Active gravel area (m^2)	Vegetated area (m^2)	Bar area (m^2) (Number)	Braid bar/ island area (m^2) (Number)	Channel area (m^2)	Total channel environment area (m^2)	Estimated mean daily discharge ($m^3 s^{-1}$)
Long-term study: data derived from maps and aerial photographs							
1836	n.d.	n.d.	n.d.	0 (0)	27 036	27 036	n.d.
1840	n.d.	n.d.	n.d.	0 (0)	23 727	23 727	n.d.
1884	6859	0	3327 (1)	3532 (3)	15 854	22 713	n.d.
1903	9219	0	6099 (1)	3120 (2)	11 133	20 352	n.d.
24/3/48	*11 517*	*0*	*11 474 (3)*	*43 (2)*	*13 509*	*25 026*	*n.d.*
11/5/51	*15 996*	*0*	*15 356 (3)*	*640 (1)*	*13 448*	*29 444*	*n.d.*
1963	0	0	0 (0)	0 (0)	12 720	12 720	n.d.
6/5/75	*357*	*16 087*	*30 (1)*	*12 527 (5)*	*17 882*	*18 179*	*3·66*
16/4/81	*877*	*14 152*	*172 (1)*	*14 857 (2)*	*16 130*	*17 007*	*2·36*
24/4/84	*2215*	*13 096*	*216 (1)*	*15 095 (6)*	*14 436*	*16 651*	*1·34*
Short-term study: data derived from ground survey							
2/8/90	1650	14 733	720 (4)	15 663 (10)	15 904	17 554	2·50
5/2/91	1866	14 509	490 (4)	15 885 (11)	15 911	17 777	3·28
16/4/91	2084	14 378	515 (6)	15 947 (17)	15 898	17 982	3·61
14/6/92	2935	14 184	675 (4)	16 444 (20)	15 546	18 481	3·28
15/3/93	4703	13 886	765 (6)	17 824 (16)	14 022	18 725	1·73

survey has established the differing profiles of the two braid channels: the east channel is trapezoidal and the west channel rectangular, a phenomenon also noted by Thorne (1978). A fall in river discharge could thus have resulted in mean channel widths decreasing in the trapezoidal east channel with mean channel widths in the rectangular west channel remaining relatively constant.

SHORT-TERM PLANFORM EVOLUTION

Figure 4 illustrates short-term planform evolution at the Llandinam instability zone for five dates over a 2·5 year period. Although the full 2·0 km Llandinam instability zone was considered when analysing the long-term evolution, it was inappropriate to study the complete reach because in recent years the channel downstream of the contemporary braid zone has been subject to small-scale channelization works and gravel extraction. These have altered the natural channel geometry and planform of the downstream section of the instability zone which has responded to these works as much as to the natural evolution of the channel subsequent to the onset of braiding upstream. Therefore, in terms of the short-term channel evolution study, only the 500 m contemporary braid zone is considered.

Before the planform evolution over the 2·5 year study period is discussed, it is appropriate to identify planform change between 1984 and the first short-term planform survey in 1990. A comparison between the 1984 planform (Figure 2j) and the first planform survey in 1990 (Figure 4a) reveals a considerable increase in bar form complexity and bar abundance over the six year period (Table III). Since the 1984 plot is based on an

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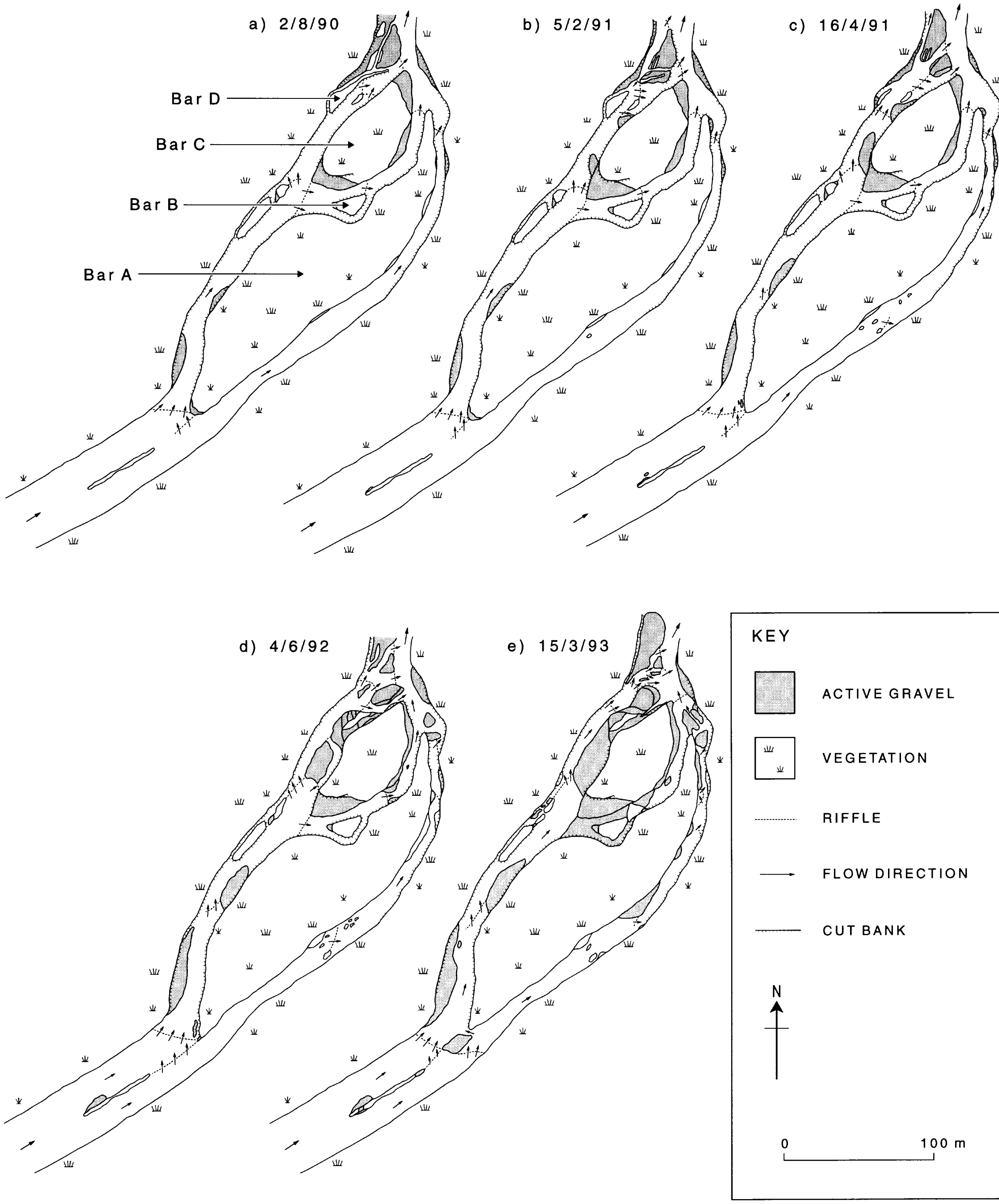

Figure 4. Channel changes in the contemporary braid zone between 1990 and 1993

aerial photo source rather than a published map source, this increase in complexity is a genuine phenomenon and not a result of detail rationalization during map production. Although the two large vegetated islands were present in 1990, other smaller vegetated islands were also in evidence, for example in the west and mid-braid channels (see Figure 1C for channel locations). Areas of active gravel had reduced in the mid-channel, partly

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through vegetation colonization, but areas of active gravel and the complexity of bar forms had increased in the west channel, especially in the lower west channel.

When analysing the short-term planform evolution of a study reach, such as at Llandinam, various scales of analysis are possible ranging from an individual bar unit, to individual braid channels and to the reach as a whole. Over the 2·5 year study period there was no significant change in gross planform; the reach remained braided. However, significant changes were observed both at the individual braid channel scale and the individual bar scale, and so study of reach evolution from August 1990 to March 1993 focused on changes at these two scales.

The second planform survey in February 1991 illustrates that during the preceding six months, only the lower west channel experienced significant channel and bar form change (Figure 4b). In the lower west channel a gravel lobe developed from the gravel head of island C (see Figure 4a for bar coding), and this had a number of direct effects on the lower west channel. First, a small lateral bar attached to island C developed in the lee of the gravel lobe. Second, the gravel lobe deflected the channel flow toward the west bank of the west channel locally causing up to 1 m of bank erosion. Finally, the deflected west channel flow also effected considerable erosion of island D; a chute channel breached its downstream limb and considerably expanded the small 1990 chute channel that cut across the gravel bar in the downstream main channel. The downstream remnant of island D became a focus of sedimentation and formed the core of a new gravel bar in the mouth of the lower west channel.

The third survey (16/4/91), just two months after survey 2, illustrates a reinforcement of the bar forms that had developed by survey 2 (Figure 4c). The gravel lobe attached to island 'C' had expanded both laterally and downstream, further deflecting flow toward the west bank and causing local bank erosion of up to 2 m and further attrition of bar D. Sediment supply from this bank erosion promoted further deposition of the lateral bar attached to island C. Medial bars in the lower main channel confluence zone had prograded downstream and had their upstream areas truncated by the scour and downstream migration of the lower west channel pool. In addition, the chute channel separating these two bars had expanded and reoriented to a more northerly direction. Activity in the rest of the study reach during this period was minimal, but one other event is worthy of note. The two lateral bars in the upper west channel had both increased in area and prograded downstream. This bar expansion occurred in conjunction with increased erosion on the banks opposite these deposits (<0·5 m) and an increase in channel sinuosity.

By survey 4 (14/6/92), bar forms and channel patterns at the Llandinam braid zone had significantly altered (Figure 4d). During the 14 month period between surveys 3 and 4, the gravel lobe had become detached from island C and formed a discrete medial bar. Channel flow was deflected to both sides of the bar effecting considerable bank erosion and channel expansion: the mean channel width at this location increased from 15·6 m (16/4/91) to 25·8 m (14/6/92). The downstream effects of this gravel lobe detachment were significant both in the lower west channel and lower main channel. Large spreads of gravel, mainly derived from upstream bank erosion and channel expansion, were deposited on the lateral bar attached to island C, increasing its area to such an extent (three-fold increase) that it coalesced with a small vegetated island. The combined effects of channel widening around the detached gravel lobe and flow deflection by the new composite lateral bar also effected the erosion and complete removal of island D. With this island removed, the lower west channel was free of bar forms on the west bank and flows were rapidly transferred to the confluence zone of the lower main channel. In the confluence zone, one medial bar had remained relatively unchanged in form but had increased in area by 40 per cent. The second medial bar, however, had been dissected into a number of smaller medial bars by the confined flow emanating from the lower west channel.

Areas of channel or bar activity in other parts of the braid zone were relatively small during the 14 month period between surveys 3 and 4. The two bars in the upper west channel had continued to prograde downstream and increased in area by between 70 and 80 per cent, thus continuing to deflect flow onto the opposite bank and cause local bank erosion of up to 5 m. A small gravel lobe had developed on the elongate medial bar in the upstream main channel and bar formation had also occurred at the confluence zone between the east and mid-braid channels.

The final planform survey (15/3/93) illustrates a dramatic shift in water flow through the braid zone (Figure 4e). All the upper west channel discharge was now routed into the lower west channel with no flow entering the

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mid-channel. The apparent abandonment of the mid-channel might be explained by one, or a combination, of the following. First, gravel accretion on the riffle at the mouth of the mid-channel may have raised the bed of the mid-channel to such an extent that, under normal flow conditions, channel discharge in the west channel no longer overtopped the riffle, with the effect of isolating the mid-channel from any water input. Second, bed scour in the west channel, particularly adjacent to the mid-channel, may have increased the discharge necessary in the west channel to overtop the riffle at the mouth of the mid-channel. Finally, channel discharge at the time of the planform survey may have been lower than on previous surveys, thus exposing more extensive areas of gravel with insufficient flow stage to overtop the mid-channel riffle. This explanation is supported by the low mean daily flow on the survey day (Table III). However, data from channel profiles across the mid-channel riffle and across the west channel opposite the mid-channel indicate that the first two explanations may also have merit. Although over the 2·5 year study period there was only a mean vertical accretion of 4 cm on the mid-channel riffle, there was a corresponding mean incision of 10·5 cm into the west channel bed. The combined effects of incision in the west channel and accretion in the mid-channel produced an effective 14·5 cm increase in the height differential between the channel beds in the west and mid-braid channels, an increase quite sufficient to route a greater proportion of the discharge into the lower west channel and to cause the abandonment of the mid-channel during periods of low trunk stream discharge. The evidence would seem to suggest that a combination of these three explanations is responsible for the abandonment of the mid-channel at the time of survey 5.

Other significant channel and bar form changes occurred during the nine months between surveys 4 and 5. A large complex lateral bar sequence was attached to the western bank of island C, formed from the coalescence of three individual bar units. Lateral growth of the large medial bar in the confluence zone also resulted in its attachment to island C. The end result of this phase of gravel accretion in the lower west channel was to join all the bar forms and attach them to island C, thus protecting the west bank of this island from further erosion. In the confluence zone itself, the dissected medial bar remained as a number of individual bar units, but the largest bar of this group increased in area by 65 per cent.

In summary, channel change at Llandinam over the 2·5 year study period illustrates three main forms of adjustment. First, channel abandonment which has been both abrupt (mid-channel between surveys 4 and 5) and gradual (east channel over the entire study period). Second, development of multiple small-scale and probably transient bars (lower west and lower main channels) which may grow and coalesce with each other and with bank sections. Finally, flow deflection by lateral bars (upper west channel) and lobe units (lower west channel) has caused increased channel sinuosity and channel expansion, respectively. All these changes are clearly conditioned by the planform context inherited from earlier periods.

DISCUSSION

Channel evolution at Llandinam has been complex over the last 150 years, with the planform switching between meandering and braided forms. Both periods of braiding (the first initiated between 1840 and 1890 and the second initiated between 1951 and 1975) were primed and triggered by a combination of intrinsic and extrinsic variables.

Intrinsic controls on planform instability

Channel instability at Llandinam has been primed by a combination of three intrinsic controls; floodplain sediments, planform evolution and channel gradient. First, the 300 m to 400 m wide floodplain at Llandinam is topographically complex (terraces and palaeochannels) but generally of low relief: over 85 per cent is less than 2·0 m above present river-bed level. The channel banks comprise two main sediment facies: first, highly erodible, poorly sorted coarse basal gravels (D_{50} = 67 mm) with a fine gravel matrix; second, a relatively thin veneer of cohesive overbank silts and clays. The preferential removal of the erodible basal gravels makes these composite banks subject to a number of failure mechanisms including shear, beam and tensile failure (Thorne and Lewin, 1979). These failure mechanisms involve the removal of large blocks of bank material resulting in relatively high rates of bank retreat and the local provision of potential bar and bedform material. The instability zone is bounded upstream by an entrenched (*c*. 2·5 m) locally bedrock-controlled reach and also bounded

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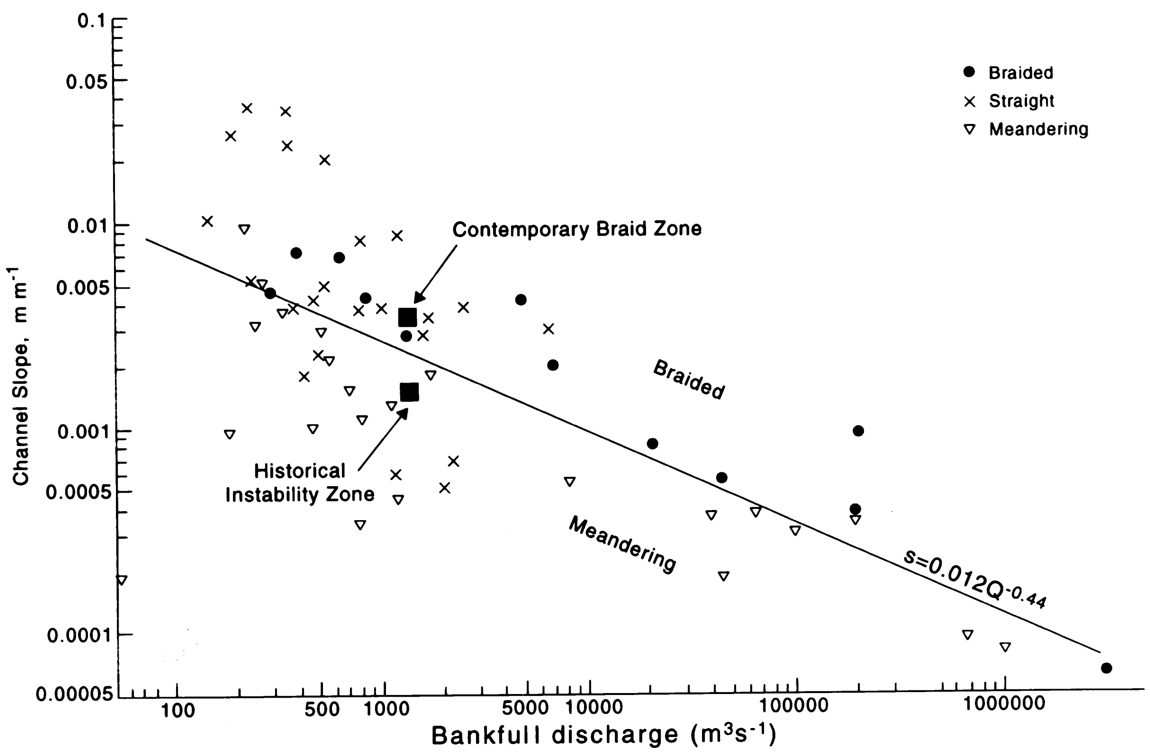

Figure 5. Channel slope versus bankfull discharge plot for selected straight, meandering and braided rivers (based on Knighton and Nanson, 1993) including the Severn contemporary braid zone and the historical instability zone

downstream by a short entrenched reach (*c*. 2·0 m). The bank material in these entrenched reaches is dominated by cohesive silts and clays and so lateral channel mobility is severely limited. Thus, the low-relief floodplain and erodible composite banks within the instability zone combine to make it inherently more unstable than the entrenched reaches, and relatively self-contained in terms of bed sediment transfers.

Second, rapid meander development between 1836 and 1840 (Figure 2a, b) confirms the presence of highly erodible bank materials and suggests that meander development by extension and translation continued after 1840. It is probable that this channel development culminated in a 'cut-off' of one or both of the meander bends, a process observed at a number of nearby sites on the River Severn (Lewis and Lewin, 1983). The net effect of a cut-off is to increase channel gradient and thereby increase stream power (see below). It is possible that post-cut-off stream powers, combined with erodible banks, may have been sufficient to trigger channel metamorphosis to a braided planform in the late nineteenth century. Braiding initiation after meander cut-off has been observed elsewhere on the Severn (e.g. Berriew; Passmore et al., 1993) but it is not a frequently observed response and channels may simply retain their new low sinuosity form with little subsequent adjustment (Lewis and Lewin, 1983). There is no evidence that meander cut-off contributed to the initiation of braiding between 1963 and 1975.

Finally, analysis of plots which attempt to discriminate different channel planforms on the basis of various hydrological, sedimentological and channel parameters indicate that braided channels usually have higher bed gradients than meandering channels (Leopold and Wolman, 1957; Schumm and Khan, 1972; Knighton and Nanson, 1993). Comparison of the instability zone channel gradient (0·00210) with the channel gradients of the upstream and downstream entrenched reaches (0·00110 and 0·00120, respectively) reveals that the Llandinam instability zone conforms to the expected pattern. However, comparison of the instability zone channel gradient and bankfull discharge data with previously published slope–discharge plots (Figure 5) reveals that the Llandinam instability zone would plot with meandering channels, well below the meandering/braiding threshold line. Even if the bankfull discharge (39·6 $m^3 s^{-1}$) were substituted for the largest estimated flood

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Table IV. Gauging station location and flow data availability in the upper Severn basin

Gauging station	National Grid reference	Catchment area (km^2)	Distance from Llandinam (km)	Continuous flow record period	Peak flow record period
Dolwen	SN996852	187	4 (upstream)	Sept 1978–Dec 1983	None
Abermule	SO164958	580	30 (downstream)	Oct 1962–present	None
Welsh Bridge	SJ489128	2287	110 (downstream)	1950–present	1672–present

discharge (*c*. 60 m^{3}s^{-1}), the instability zone would still plot below the meandering braiding threshold. If the pattern of channel gradients at the contemporary braid zone scale is considered, then a similar situation emerges. Channel gradients immediately upstream and downstream of the braid zone (0·00035 and 0·00068, respectively) are significantly lower than the channel gradient of the west branch in the braid zone (0·00442). However, in contrast to the whole instability zone, a bankfull discharge of 39·6 m^{3}s^{-1} and a channel gradient of 0·00442 would plot the contemporary braid zone with other braided channels, just above the meandering/braiding threshold (Figure 5).

In summary, the Llandinam instability zone is characterized by a channel with a relatively high bed gradient (accentuated by meander cut-off) which is laterally bounded by highly erodible low elevation banks. The potential for channel mobility is therefore high, especially in relation to the entrenched upstream and downstream reaches. But although intrinsic controls have made the reach inherently unstable, it is believed that extrinsic mechanisms have been ultimately responsible for triggering channel metamorphosis (meandering to braiding).

Extrinsic triggers of planform instability

Channel metamorphosis in response to changes in hydrological regime, especially flooding, is a well documented phenomenon (Vogt, 1963; Burkham, 1972; Graf, 1983; McEwen, 1989; Hooke, 1996). Although fluvial responses to flooding are not uniform, they generally result in channel destabilization and increased sediment movement. Unfortunately, continuous flow data for the upper Severn basin are patchy, with stations near to Llandinam (e.g. Dolwen) having only limited flow archives (Table IV). Welsh Bridge at Shrewsbury has the longest and potentially most valuable flow record but its distance from Llandinam makes flow reconstructions at Llandinam based on those data potentially hazardous. However, detailed analysis of overlapping flow records has revealed that significant correlations exist between the peak daily flows at Dolwen and Abermule ($r = 0{\cdot}96$; significant at $\rho = 0{\cdot}01$) and between the flows at Abermule and Welsh Bridge ($r = 0{\cdot}77$; significant at $\rho = 0{\cdot}01$). On the basis of these strong correlations, expected flows at Dolwen were calculated from 1991 to 1994 using linear regression analysis. Reconstructed flows at Dolwen were found to correlate strongly with flows at Welsh Bridge ($r = 0{\cdot}87$; significant at $\rho = 0{\cdot}01$) giving the opportunity of using the flow data at Welsh Bridge as a proxy record for the flood history at Llandinam. It should be noted that although this approach provides a reliable measure of the *timing* of flooding, event *magnitude* may be underestimated because relatively few high flow events are used in the regression analysis.

Figure 6 shows the flood history (peak flows >400 m^{3}s^{-1}) at Welsh Bridge, Shrewsbury, from 1672 to the present. A discharge of 400 m^{3}s^{-1} at Welsh Bridge corresponds to a discharge of *c*. 37 m^{3}s^{-1} at Dolwen, a discharge just below bankfull at Llandinam (39·6 m^{3}s^{-1}; Costa, pers. comm.). Known phases of meandering and braiding at Llandinam occupy a relatively small part of the flood history, and for the most part archival evidence does not permit a full planform reconstruction at the site.

Analysis of the River Severn flood history reveals that flood timing and flood magnitude have differed between pre- and post-braiding phases (Figure 6). Prior to both documented phases of braiding at Llandinam (1890–1903 and 1975–present) there were increases in both flood frequency and magnitude (1849–1886 and 1948–1965). Both these periods of increased hydrological activity were characterized by some of the largest Severn floods on record, for example 1869, 1881, 1960, 1964 and 1965 (Harding, 1972). Other British rivers also experienced a similar pattern of increased flood frequency and magnitude in the late nineteenth and early

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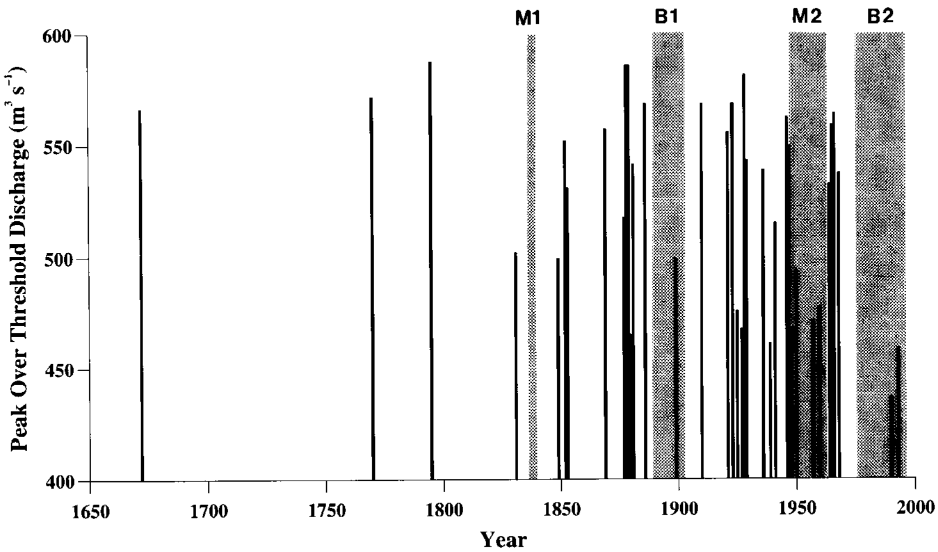

Figure 6. Flood record (peak over threshold: 400 $m^3 s^{-1}$) at Welsh Bridge (Shrewsbury) from 1672-1997. M1 and M2 show two periods of known meandering and B1 and B2 show two periods of known braiding at Llandinam

twentieth centuries coupled with channel destabilization. For example, phases of braiding on the South Tyne have been related to increased hydrological activity stimulated by land use and climate change (Passmore *et al.*, 1993) and McEwen (1989) noted an increase in braiding on some Scottish rivers in response to higher flood frequencies between 1869 and 1902. These studies, and the data from Llandinam, indicate that phases of braiding can be facilitated, if not triggered, by increased flood frequency and magnitude.

The early decades of the twentieth century were marked by a period of reduced hydrological activity and rivers responded by developing more stable planforms. At Llandinam, the planform adjusted from its former braided pattern to a single thread, low sinuosity pattern. Although flood frequency and magnitude generally declined between 1910 and 1960, there were still a number of notable floods (1946, 1947 and 1948). It is interesting to note that these floods did not trigger a new phase of braiding in the late 1940s (Figure 2); instead this period was characterized by an increase in channel stability. McEwen (1989) also noted this phenomenon in the upper Dee catchment and it seems that as channels adjust to more stable forms after channel metamorphosis events (e.g. meandering to braiding), floods that might have triggered instability prior to metamorphosis can contribute to the re-establishment of a quasi-equilibrium form (Wolman and Gerson, 1978).

It is perhaps worth making the point that the causes of changes in flood frequency on the Severn have been ascribed to alternative explanations. Howe et al. (1967) placed emphasis on the role of afforestation and land drainage in altering flood magnitude and frequency, although the decrease in magnitude of large floods since their studies (see Figure 6) may suggest otherwise. Phases of high and low flood frequency may occur within climatic regimes, as shown for example by Warner (1987) in eastern Australia. Thus changes extrinsic to the channel-forming process are not necessarily extrinsic to hydrological regimes over a longer period of time (see Higgs (1987) for an account of climate fluctuations on the upper Severn).

After the onset of the second phase of braiding, triggered by two large floods in 1964 and 1965, the River Severn again experienced a period of reduced hydrological activity which has in turn promoted channel stability. This channel stability at Llandinam has been promoted via two additional mechanisms. First, channel management involving realignment and revetments in the downstream half of the zone has confined lateral mobility. Second, flood frequency and magnitude have reduced over the last 30 years with only two floods exceeding 400 $m^3 s^{-1}$ at Welsh Bridge since 1967 (Figure 6). This change in hydrological regime in the upper Severn is a response to both climatic fluctuation (Higgs, 1987) and to flow regulation imposed since 1968 on the Afon Clywedog, a major tributary of the River Severn. For example, since 1968 there has been a 25 per cent decrease in the mean annual flood discharge, and flood events (>115 $m^3 s^{-1}$) have reduced from 2·61 to 1·80 per

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annum (Higgs, 1987). Since the hydrological regime of the River Severn has been demonstrated to be influential in triggering phases of braiding, the current hydrological regime may constrain or even prevent future braiding episodes. What is already apparent is the way in which flow control on the River Severn is affecting the recovery of the contemporary braid zone at Llandinam. Since exceptionally high flows (sufficient to trigger braiding) and moderately high flows (sufficient to promote rapid meander growth) are now restricted, if not eliminated altogether, channel adjustments at the reach scale are now controlled by intermediate flows which only allow relatively minor channel changes (small bar development, local bank erosion and channel switching/blocking). Flow regulation immediately following the incidence of braiding appears to have partly ‘frozen’ the instability zone, in particular the contemporary braid zone, a fact supported by the unchanged channel planform since 1975 (Figure 2). Such channel pattern ‘freezing’ clearly complicates an appraisal of whether the meandering–braiding transition might be marked by a threshold at Llandinam.

The Llandinam planform threshold?

Although there is agreement as to the existence of thresholds and their effect on geomorphic processes (Bull, 1991), there are differences of opinion as to the applicability of the threshold concept to channel planform. Newson (1992) has reviewed the main aspects of the debate and highlights the fact Leopold and Wolman’s (1957) seminal paper is remembered for its graphical discrimination between braided and meandering channels (often interpreted as a process threshold) even though the authors emphasize that channel patterns form a continuum. Although Leopold and Wolman’s distinction between meandering and braiding is based on only two variables (discharge and slope), and hence has obvious limitations (Carson, 1984), the Llandinam data broadly fit with the graphical model: the current, broadly meandering, instability zone plots with other meandering channels whereas the contemporary braid zone plots with other braided channels.

Bull (1991) produced a theoretical threshold equilibrium plot showing how stream-bed altitude might respond to threshold events over time. Figure 7a utilizes this approach to illustrate how a channel planform might change from meandering to braiding in response to a threshold event (e.g. a flood). An initially meandering channel might react very quickly to a flood event (R_a = reaction time) but then take some time a establish a new equilibrium form (R_x = relaxation time). The new equilibrium form may persist for some time (P_s = persistence time) before a second threshold event destabilizes the system again. Figure 7b illustrates the application of the threshold–equilibrium concept to the long-term planform history at Llandinam. Although archival evidence does not permit a full temporal reconstruction of channel planforms, previous discussion has demonstrated the link between phases of braiding and high magnitude floods, and so planform reaction times were probably very short. The relaxation time of the first braiding phase was between 19 and 64 years, although archival evidence would suggest the actual duration was closer to the former figure. The relaxation time of the second braiding phase is unknown, but it has already lasted for at least 22 years and probably nearer 32 years. Previous discussion has suggested that the contemporary braid zone is now partly ‘frozen’ in response to flow regulation, probably resulting in an extended persistence time (Figure 7b). However, as future discussion will suggest, the cumulative effects of small-scale channel changes within the braid zone are capable of returning the reach back to a single thread channel within the foreseeable future.

The question of whether such a reversion to a single thread channel involves crossing a planform threshold, however, still remains. Gilvear (1993) suggested that many UK rivers lie close to the transitional boundary between single thread and braided channels and as such are highly sensitive to changes in flow regime, sediment supply and management practices. McEwan (1989) provided evidence for this belief by suggesting that flood-induced phases of braiding on some Scottish rivers were associated with threshold crossing. The fact that the meandering planform present in the 1940s and 1950s broadly corresponds with the meandering planform present in 1836 and 1840 might suggest that channel change at Llandinam is better explained by a continuum approach. However, the onset of braiding is apparently rapid compared to the relatively slow reversion to meandering, and this type of pattern change accords with conventional definitions of threshold events (Newson, 1992). Although evidence exists to support both a continuum and a threshold view of channel changes at Llandinam, current understanding of channel dynamics does not permit an unequivocal answer for Llandinam.

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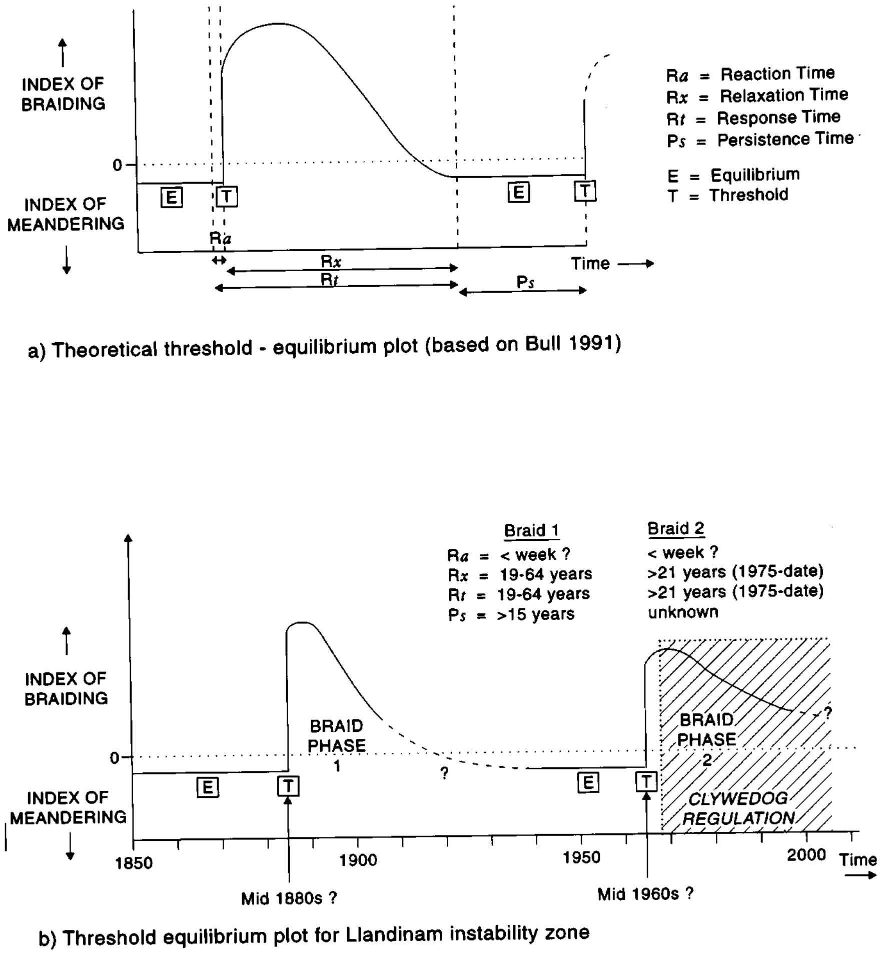

Figure 7. Threshold equilibrium plots for channel change. (a) Theoretical plot illustrating a transition from meandering to braiding (based on Bull, 1991). (b) A plot for Llandinam showing the two meandering phases and the two braiding phases

The issue of how to distinguish planform changes marked by a threshold and those existing on a continuum still needs to be resolved.

Future patterns of planform instability

From the preceding discussion it is apparent that the current phase of braiding is quite distinct from the earlier phase of braiding at the end of the nineteenth century. Braiding is now confined to a relatively small part of the instability zone and planform adjustments within the zone have been minimal since 1975. However, small-scale channel adjustments have increased the area of active gravel within the contemporary braid zone since the onset of braiding (Table III). In spite of reduced hydrological activity, intrinsic controls on channel stability appear to be exercising a significant influence at Llandinam. The phase of braiding initiated between 1963 and 1975 exploited a pre-existing ephemeral chute channel across a lateral bar (Figure 2g). This chute channel ultimately became the west channel in the new braid zone (Figure 1C) and over time has steadily captured more and more flow from the east channel (the former single thread channel in 1963). This flow capture has been facilitated by the relatively high bed gradient across the riffle at the head of the upper west channel. Over the 2·5 year monitoring programme in this study (1990–1993) the increasing dominance of the west channel was noted. Field measurements indicated that over 80 per cent of the flow entering the instability zone was funnelled into the upper west channel. This discharge imbalance has influenced the relative stream powers and thus the sediment mobility and bank erosion in the two channels. Sediment mobility for D_{50} clasts,

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as determined by tracers, was significantly higher in the west channel with average step lengths of 26 m compared with only 5 m in the east channel. There was no recorded bank erosion in the east channel over the study period. However, in the upper west channel, bank erosion was concentrated on the west bank (mean retreat 1·50 m) with only minor erosion on the east bank (0·25 m). In contrast, channel expansion in the lower west channel caused high rates of bank retreat of both the west and east banks (8·70 and 3·20 m, respectively).

Having established the long-term planform evolution of the instability zone and identified the nature of current channel activity in the contemporary braid zone, it is possible to make some predictions about likely future channel changes at Llandinam. Judging by the rate of flow capture by the west channel over the last 20 years it is likely that the east channel will be abandoned within the next 10 years. The complete flow capture by the west channel will effectively return the contemporary braid zone to a single thread channel once again (assuming the mid-channel is not reoccupied) and result in rapid channel adjustment in the west channel. Two scenarios for this expected channel adjustment are proposed.

1. A high-sinuosity single thread channel evolves. Bank erosion would concentrate on the west bank of the upper west channel and on the east bank of the lower west channel. Flow regulation may make this a smaller scale iterative process than would otherwise be the case.
2. A new phase of braiding is initiated. Bank erosion would concentrate on the west bank of the upper west channel and channel expansion would occur in the lower west channel. The high bed gradient in the lower west channel combined with an abundant sediment supply from bank erosion would be sufficient to maintain and develop a braided channel network, provided that large-magnitude floods still occur with a regulated Clywedog.

In both cases it is envisaged that the focus of instability will move downstream. Over the study period, downstream migration of gravel bars in the lower main channel (confluence zone) was observed. This resulted in enhanced erosion on the 90° bend immediately downstream of the contemporary braid zone. If braiding is maintained in the lower west channel (scenario 2) it is expected that it will extend downstream to occupy a position between the contemporary braid zone and the 1884/1903 braid location. Such mobility of unstable channel zones within alluvial areas has been noted on other rivers (e.g. River South Tyne; Macklin and Lewin, 1989) and there are clear implications for channel managers, especially at Llandinam where such a migration would impinge on the managed reach.

Channel adjustments at Llandinam in the foreseeable future will be accomplished within a hydrological regime of reduced activity, imposed in particular by Clywedog Dam. Although several Global Circulation Models predict increases in the amount of precipitation and its intensity in northern Europe (Newson and Lewin, 1990), careful management of water releases from Clywedog Dam should be able to initially control the expected 'flashier' hydrograph in the upper Severn basin. However, since Clywedog regulates flow from only 26 per cent of the catchment area at Llandinam it is likely that the dam's flood reduction capabilities at Llandinam will steadily reduce under wetter climatic conditions. Expected increases in flood frequency and magnitude in the coming decades will pose significant problems for channel managers not only in terms of flood water routing but also in terms of dealing with channel adjustments. If the predictions made in this paper are valid then intrinsic controls on channel change at Llandinam (floodplain sediments, planform history and channel gradient) may prime the reach for another phase of braiding. Although braiding may persist or be reinitiated via intrinsic controls, flood frequency and magnitude are currently insufficient to destabilize the reach and thus force a threshold response. A comparison between the former longer term channel change record (150 years) with shorter term change (since 1990) suggests caution in predicting channel change on partially regulated rivers. Flood frequency changes can be related to pattern metamorphosis in the longer term, but pattern 'freezing' in recent decades, in the context of greater regulation of discharges, makes the effects of climatic changes rather more difficult to predict.

CONCLUSIONS

Channel planform evolution over the last 150 years at Llandinam has involved alternating phases of meandering and braiding and has demonstrated the complex and variable nature of channel change over time. Early

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planform adjustments involved the whole 2·0 km instability zone with a relatively high sinuosity channel in 1840 replaced with a braided channel by 1890 and later replaced by a meandering channel by 1948. Later surveyed planform adjustments involved only a small part of the reach, with a 500 m braid zone situated within a quasi-stable low sinuosity meandering reach since 1975. Since 1990 there have been only relatively small-scale changes within the contemporary braid zone, the larger instability zone appearing to be broadly stable.

Episodes of channel destabilization have been shown to be linked with both intrinsic and extrinsic controls. Intrinsic controls have made the Llandinam reach inherently unstable and have thus 'primed' it for instability, whereas extrinsic controls, most notably flooding, have been responsible for actually 'triggering' phases of instability (braiding). High magnitude floods on the pre-regulated River Severn are believed to be the most important cause of channel instability over the last 150 years. Since the mid-1960s, changes in climate, and flow regulation imposed by Clywedog Dam, have brought about a reduction in hydrological activity, resulting in a 'part-freezing' of the channel planform at Llandinam. This planform 'freezing' poses a management challenge since it is difficult to predict how a combination of future climate changes and flow control will affect the flow regime, and thus channel instability, in the upper Severn basin. There is clearly a need to identify other reaches which seem to be inherently unstable and which appear to exhibit a threshold potential.

This study has suggested that the process of adjustment to environmental change (particularly where metamorphosis occurs) involves three principles. Environmental change, for example arising from global climatic change, will be *phased in* over time to an already changing channel system, in much the same way as Clywedog regulation impacted upon the river. The effects of that change were *historically contingent* upon the particular state of the channel at the time of impact (the channel being braided in 1968 but relaxing towards a meandering state). Future changes will be similarly contingent, and to be understood will require longer term surveys of channel form development to establish the context for environmental change impact assessment. Particularly where there have already been major extrinsic changes (for example arising from river regulation), it is important to appreciate that what is observed over the short term can be *partially frozen* channel patterns – in outline dependent on major previous events and prior regimes, but being modified in detail as regulated conditions allow.

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REFERENCES

Brice, J. C. 1964, *Channel patterns and terraces of the Loup rivers in Nebraska*, U.S. Geological Survey Professional Paper **422D**.

Brice, J. C. 1984. 'Planform properties of meandering rivers', in Elliot, C. M. (Ed.), *Proceedings of the Conference – Rivers '83*, American Society of Civil Engineers, New Orleans, 1–15.

Brookes, A. 1987. 'River channel adjustments downstream from channelization works in England and Wales', *Earth Surface Processes and Landforms*, **12**, 337–351.

Bull, W. B. 1991. *Geomorphic Responses to Climatic Change*, Oxford University Press, New York, 326 pp.

Carson, M. A. 1984. 'The meandering–braided river threshold: a reappraisal', *Journal of Hydrology*, **73**, 315–334.

Church, M. 1983. 'Pattern of instability in a wandering gravel bed channel', in Collinson, J. D. and Lewin, J. (Eds), *Modern and Ancient Fluvial Systems*, IAS Special Publication **6**, 169–180.

Dury, G. H. 1970. 'General theory of meandering valleys and underfit streams', in Dury, G. H. (Ed.), *Rivers and River Terraces*, Macmillan, London, 264–275.

Erskine, W. D. and Warner, R. F. 1988. 'Geomorphic effects of alternating flood- and drought-dominated regimes on the N.S.W. coastal rivers', in Warner, R. F. (Ed.), *Fluvial Geomorphology in Australia*, Academic Press, Sydney, 223–244.

Ferguson, R. 1987. 'Hydraulic and sedimentary controls of channel pattern', in Richards, K. (Ed.), *River Channels. Environment and Process*, IBG Special Publication **17**, 129–158.

Ferguson, R. 1993. 'Understanding braiding processes in gravel-bed rivers: progress and unsolved problems', in Best, J. L. and Bristow, C. S. (Eds), *Braided Rivers*, Geological Society Special Publication **75**, 73–87.

Graf, W. L. 1983. 'Flood-related channel change in an arid-region river', *Earth Surface Processes and Landforms*, **8**, 125–139.

Harding, D. M. 1972. *Floods and Droughts in Wales*, PhD thesis, University of Wales, Aberystwyth, 501 pp.

Harley, J. B. 1965. 'The re-mapping of England, 1750–1800', *Imago Mundi*, **19**, 56–67.

Harley, J. B. 1975. *Ordnance Survey Maps, a Descriptive Manual*, Ordnance Survey, Southampton, 200 pp.

Higgs, G. 1987. 'Environmental change and hydrological response: flooding in the upper Severn catchment', in Gregory, K. J., Lewin, J. and Thornes, J. B. (Eds), *Palaeohydrology in Practice*, Wiley, Chichester, 131–159.

Hitchcock, D. 1977. 'Channel pattern changes in divided reaches: an example in the coarse bed material of the Forest of Bowland', in Gregory, K. J. (Ed.), *River Channel Changes*, Wiley, Chichester, 207–220.

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Hooke, J. M. 1977. 'The distribution and nature of change in river channel patterns: the example of Devon', in Gregory, K. J. (Ed.), *River Channel Changes*, Wiley, Chichester, 265–280.
Hooke, J. M. 1986. 'The significance of mid-channel bars in an active meandering river', *Sedimentology*, **33**, 839–850.
Hooke, J. M. 1996. 'River responses to decadal-scale changes in discharge regime: the Gila River, SE Arizona', in Branson, J., Brown, A. G. and Gregory, K. J. (Eds), *Global Continental Changes: the Context of Palaeohydrology*, Geological Society Special Publication **115**, 191–204.
Hooke, J. M. and Kain, R. J. P. 1982. *Historical Changes in the Physical Environment*, Butterworths, London, 236 pp.
Howe, G. M., Slaymaker, H. O. and Harding, D. M. 1967. 'Some aspects of the flood hydrology of the upper catchments of the Severn and Wye', *Transactions of the Institute of British Geographers*, **41**, 33–58.
Humphries, A. M. 1979. *The Quaternary deposits of the Upper Severn Basin and adjoining areas*, PhD thesis, University College of Wales, Aberystwyth.
Knighton, A. D. and Nanson, G. C. 1993. 'Anastomosis and the continuum of channel pattern', *Earth Surface Processes and Landforms*, **18**, 613–625.
Knox, J. C. 1983. 'Responses of river systems to Holocene climates' in Wright, H. E. Jr (Ed.), *Late Quaternary Environments of the United States, Volume 2, The Holocene*, Geological Society of America, Boulder, Colorado, 26–41.
Lawler, D. M. 1992. 'Design and installation of a novel automatic erosion monitoring system, *Earth Surface Processes and Landforms*, **17**, 455–464.
Leddy, J. O., Ashworth, P. J. and Best, J. L. 1993. 'Mechanisms of anabranch avulsion within gravel-bed braided rivers: observations from a scaled physical model', in Best, J. L. and Bristow, C. S. (Eds), *Braided Rivers*, Geological Society Special Publication **75**, 119–127.
Leigh, D. S. and Feeney, T. P., 1995. 'Paleochannels indicating wet climate and lack of response to lower sea level, southeast Georgia', *Geology*, **23**, 687–690.
Leopold, L. B. and Wolman, M. G. 1957. *River channel patterns: braided, meandering and straight*, US Geological Survey Professional Paper **282B**.
Lewin, J. 1976. 'Initiation of bedforms and meanders in coarse-grained sediments', *Geological Society of America Bulletin*, **87**, 281–285.
Lewin, J. 1977. 'Channel pattern changes', in Gregory, K. J. (Ed.), *River Channel Changes*, Wiley, Chichester, 167–184.
Lewin, J. 1983. 'Changes of channel patterns and floodplains', in Gregory, K. J. (Ed.), *Background to Palaeohydrology*, Wiley, Chichester, 303–319.
Lewin, J. 1987. 'Historical channel changes', in Gregory, K. J., Lewin, J. and Thornes, J. B. (Eds), *Palaeohydrology in Practice*, Wiley, Chichester, 161–175.
Lewis, G. W. and Lewin, J. 1983. 'Alluvial cutoffs in Wales and the Borderlands', in Collinson, J. D. and Lewin, J. (Eds), *Modern and Ancient Fluvial Systems*, Special Publication of the International Association of Sedimentologists **6**, 145–154.
Macklin, M. G. and Lewin, J. 1989. 'Sediment transfer and transformation of an alluvial valley floor: the River South Tyne, Northumbria, UK', *Earth Surface Processes and Landforms*, **14**, 233–246.
Macklin, M. G. and Lewin, J. 1993. 'Holocene river alluviation in Britain', *Zeitschrift für Geomorphologie*, Supplement Band **88**, 109–122.
Macklin, M. G., Passmore, D. G. and Newson, M. D. 1998. 'Controls of short term and long term instability: processes and patterns in gravel-bed rivers, the Tyne Basin, North England', in Klingerman, P. C., Beschta, R. L., Komar, P. D. and Bradley, B. (Eds), *Gravel-Bed Rivers in the Environment*, Oregon University Press (in press).
Martin, Y. and Church, M. 1995. 'Bed-material transport from channel surveys: Vedder River, British Columbia', *Earth Surface Processes and Landforms*, **20**, 347–361.
McEwen, L. J. 1989. 'River channel changes in response to flooding in the Upper River Dee catchment, Aberdeenshire, over the last 200 years', in Beven, K. and Carling, P. (Eds), *Floods: Hydrological, Sedimentological and Geomorphological Implications*, Wiley, Chichester, 219–238.
Nanson, G. C. 1980. 'Point bar and floodplain formation of the meandering Beatton River, northwestern British Columbia, Canada', *Sedimentology*, **27**, 3–29.
Nanson, G. C. and Knighton, A. D. 1996. 'Anabranching rivers: their cause, character and classification', *Earth Surface Processes and Landforms*, **21**, 217–239.
Neill, C. R. 1973. *Hydraulic and morphologic characteristics of Athabasca River near Fort Assiniboine*, Highway River Engineering Division Report, **REH/73/3**, Alberta Research Council, Edmonton.
Newson, M.D. 1992. 'Geomorphic thresholds in gravel-bed rivers – refinement for an era of environmental change', in Billi, P., Hey, R. D., Thorne, C. R. and Tacconi, P. (Eds), *Dynamics of Gravel-bed Rivers*, Wiley, Chichester, 2–20.
Newson, M.D. and Lewin, J. 1991. 'Climate change, river flow extremes and fluvial erosion – scenarios for England and Wales', *Progress in Physical Geography*, **15**, 1–17.
Passmore, D. G., Macklin, M. G., Stevenson, A. C., O'Brien, C. F. and Davis, B. A. S. 1992. 'A Holocene alluvial sequence in the lower Tyne valley, northern Britain: a record of river response to environmental change, *The Holocene*, **2**, 138–147.
Passmore, D. G., Macklin, M. G., Brewer, P. A., Lewin, J., Rumsby, B. T., and Newson, M. D. 1993. 'Variability of late Holocene braiding in Britain', in Best, J. L. and Bristow, C. S. (Eds), *Braided Rivers*, Geological Society Special Publication **75**, 205–229.
Petts, G. E. 1979. 'Complex response of river channel morphology subsequent to reservoir construction', *Progress in Physical Geography*, **3**, 329–362.
Robertson-Rintoul, M. S. E. and Richards, K. S. 1993. 'Braided-channel pattern and palaeohydrology using an index of total sinuosity', in Best, J. L. and Bristow, C. S. (Eds), *Braided Rivers*, Geological Society Special Publication **75**, 113–118.
Rumsby, B. T. and Macklin, M. G. 1994. 'Channel and floodplain response to recent abrupt climate change: the Tyne Basin, Northern England', *Earth Surface Processes and Landforms*, **19**, 499–515.
Rust, B. R. 1972. 'Structure and process in a braided river', *Sedimentology*, **18**, 221–245.
Rust B. R. and Nanson, G. C. 1986. 'Contemporary and palaeochannel patterns and the Late Quaternary stratigraphy of Cooper Creek, Southwest Queensland, Australia', *Earth Surface Processes and Landforms*, **11**, 581–590.
Schumm, S. A. 1969. 'River metamorphosis', *Journal of the Hydraulics Division of the American Society of Civil Engineers*, **95**, 255–273.

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Schumm, S. A. 1973. ‘Geomorphic thresholds and complex response of drainage systems’, in Morisawa, M. (Ed.), *Fluvial Geomorphology*, State University of New York, Binghampton, New York, 299–310.
Schumm, S. A. and Khan, H. R. 1972. ‘Experimental study of channel patterns’, *Bulletin of the Geological Society of America*, **83**, 1755–1770.
Schumm, S. A. and Parker, R. S. 1973. ‘Implications of complex alluvial response of drainage systems for Quaternary alluvial stratigraphy’, *Nature*, **243**, 99–100.
Smith, N. D. 1974. ‘Sedimentology and bar formation in the upper Kicking Horse River, a braided outwash stream’, *Journal of Geology*, **82**, 205–224.
Smith, D. G. and Smith, N. D. 1980. ‘Sedimentation in anastomosed river systems: examples from alluvial valleys near Banff, Alberta’, *Journal of Sedimentary Petrology*, **50**, 157–164.
Starkel, L. 1981. ‘The evolution of the Wisloka valley near Debica during the Late Glacial and Holocene’, *Folia Quaternaria*, **53**, 41 pp.
Starkel, L. 1991. ‘The Vistula River Valley: A case study for Central Europe’, in Starkel, L., Gregory, K. J. and Thornes, J. B. (Eds), *Temperate Palaeohydrology: Fluvial Processes in the Temperate Zone during the last 15,000 years*, Wiley, Chichester, 171–188.
Thorne, C. R. 1978. *Processes of bank erosion in river channels*, PhD Thesis, University of East Anglia, Norwich, 447 pp.
Thorne, C. R. and Lewin, J. 1979. ‘Bank processes, bed material movement and planform development in a meandering river’, in Rhodes, D. D. and Williams, G. P. (Eds), *Adjustments to the Fluvial System*, 117–137.
Vogt, H. 1963. ‘Aspecte der Morphodynamik des mittleren Adour (SW-Frankreich)’, *Petermanns Gegr. Mitteilungen*, **107**, 1–13.
Warner, R. F. 1987. ‘Spatial adjustments to temporal variations in flood regime in some Australian rivers’, in Richards, K. S. (Ed.) *River Channels: Environment and Process*, Blackwell, Oxford, 14–40.
Wells, L. E. 1990. ‘Holocene history of the El Niño phenomenon as recorded in flood sediments of northern coastal Peru’, *Geology*, **18**, 1134–1137.
Werritty, A. and Ferguson, R. I. 1980. ‘Pattern change in a Scottish braided river over 1, 30 and 200 years’, in Cullingford, R. A., Davidson, D. A. and Lewin, J. (Eds), *Timescales in Geomorphology*, Wiley, Chichester, 53–68.
Wolman, M. G. and Gerson, R. 1978. ‘Relative scales of time and effectiveness of climate in watershed geomorphology’, *Earth Surface Processes*, **3**, 189–208.
Young, R. W., Nanson, G. C. and Bryant, E. A. 1986. ‘Alluvial chronolgy for coastal New South Wales climatic controls or random erosional events?’, *Search*, **17**, 270–272.

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